Cite this article
Nayak, B. K., Mathur, J., Chandra, T., Sansaniwal, S. K., Garg, V., Gupta, R. (2024). A Baseline Study for Residential Energy Consumption Using Socioeconomic and Physical Building Attributes: A Case of Jaipur. In Proceedings of Energise 2023- Lifestyle, Energy Efficiency, and Climate Action, pp 30–37, Alliance for an Energy Efficient Economy.
https://doi.org/10.62576/NDRP3861

A Baseline Study for Residential Energy Consumption Using Socioeconomic and Physical Building Attributes: A Case of Jaipur

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Highlights

- Identification of critical parameters influencing energy consumption in Indian homes, finding the correlation of selected parameters with energy consumption and EPI
- This study provides insight into energy consumption behaviour at the end-user level.

Abstract

Indian residential energy consumption increased nearly 50 times its levels in 1971. Studies have reported a wide variation between the statistically projected and actual energy consumption values in residential buildings. Access to reliable energy consumption data is limited in Indian cities. This study aims to use primary datasets to develop a baseline for residential energy consumption in India. Its first objective is to understand the prevailing practices adopted in residential energy studies. The second is to understand the contributions of socioeconomic factors to it. This research analyses 2327 primary survey samples from Jaipur. The dataset was analyzed using the multivariate statistical technique. The results highlighted the uptake in appliance ownership and its implications on energy consumption across income groups. The study has also compared the relevance of EPI (annual consumption/total area) and annual energy consumption as indicators in the building benchmarking process for Indian homes.

Keywords: baseline study, residential energy consumption, Socioeconomic factors

Introduction

Under various user conditions, the behaviour of building systems can create a wide range of variations in the energy consumption pattern. Researchers must learn about the distinctive components and their dynamics within the structural assembly of a building. Hence, it is necessary to study them and various building types at different scales [1]. With the development of better computing capacity and building energy modelling tools, accessing future consumption in various user conditions (including new technologies and materials) is becoming more accessible. With higher income levels, average household-level equipment ownership has also increased. It has significantly enhanced the volume of consumption data and created a scope for data-driven decision-making [2] for Indian homes to achieve better energy efficiency.

India is the third largest energy consumer in absolute terms; it stands at 47th in per capita energy consumption globally, which is 62% lower than the world average [3]. It indicates the vast, repressed demand potential for energy, which will eventually surface with growth in per capita income levels. Since 2000, the Indian energy sector has undergone development and reform. With increasing political focus on making electricity more accessible to all, governments (at all levels) have been interested in developing policies to facilitate this. As a result, many publicly funded surveys have been done to learn about equipment ownership, energy mix, access quality, and several similar socioeconomic factors related to energy consumption behaviour at the household level. CENSUS and NSSO are two notable national-level sampling survey agencies with reliable databases. In addition, NCAER has done two sets (2004-05 and 2011-12) of nationwide household-level sample surveys. The survey is IHDS (open database), which is currently available on the ICPSR website. This development led to independent academic studies across the country and abroad. Several of these studies have used secondary or aggregator-level datasets. Few of them have referred to the above-mentioned national-level databases. A few studies have used primary datasets obtained by surveys or intrusive monitoring. Additionally, the expansion of the real estate market in India has influenced dwelling typologies in urban areas. Hence, researchers need to look at this sector with fresh eyes and reposition its relevance in the context of future energy demand.

Methodology

Different kinds of literature use many parameters in other contexts. From a methodological point of view, it was essential for us to investigate each of them. Moreover, in an Indian context, collecting every data point may not always be feasible due to the wide variation of building types. Hence, the study intended to find out the correlation of various parameters with energy consumption reported in the literature for the Indian context. The relevant parameters are shortlisted in three stages (Figure 1).

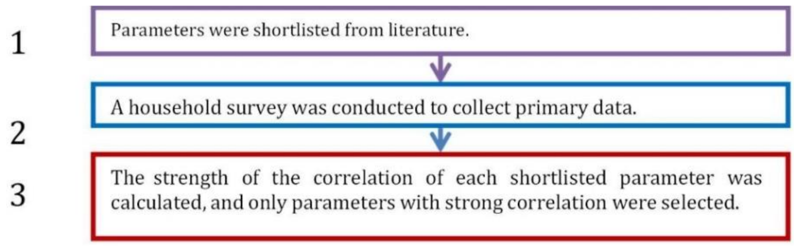

Figure 1: Methodological flow chart

Identification of relevant parameters

The parameters were shortlisted in two phases. In the first stage, a list of parameters was prepared based on the literature review. It comprised journal papers, reviewed reports (by government and non-government agencies), and national-level survey documents. The focus was more on Indian studies or studies relevant to the Indian context. Several studies from other countries were also reviewed to identify the number of possible parameters. Then, a logical assessment was done to eliminate parameters from the list. For example, studies in several countries classify building stock based on the utility companies that provide electricity connections [4]. In the Indian context, we have a single utility for each city.

Similarly, being a single-location study, the climatic context remained constant. However, this study does not discount the eliminated permanents' contribution to household energy consumption. It was a decision purely taken considering the context of this study. Hence, we strongly recommend that future researchers make their assessments before shortlisting their parameters. A reference to the processes followed in this study may be helpful for them to supplement their methodology. The final list of parameters was broadly divided into three categories: Socioeconomic, equipment, and geometric. Similar parameter classification is adopted in the TABULA project [5] and DoE [6]. However, this study also included socioeconomic data sets besides geometry, construction, system, and operation data. It is essential to note that the building specifications could be more standardized in India, unlike the U.S. and Europe. Hence, depending on standard specification data can be misleading. Moreover, socioeconomic factors like household income can significantly influence consumption behaviours. Similarly, there is no standard norm for maximum occupancy for a dwelling unit in India. Hence, these parameters need to be scrutinized. Table 1 contains the shortlisted parameters for the building stock classification.

Table 1: The table contains the shortlisted parameters

	Classification of Parameter Used for Building Archetypes				**[The shortlisted parameters]**
SR. No.	**Refereed Journals (2001 onwards)**	**Other Published Literature**	**Census of India**	**National Building Code (NBC)**	**Remarks**
1	High-rise/ Low rise	Building Height High-rise / Low rise	--	Building Height High-rise /Low rise	As per part 4, buildings above 15 meters are considered high-rise. As per the norms of NBC, fire provisions are mandatory for such buildings.
2	Age of the buildings	--	--	--	Several building classifications (energy consumption based) have used building age as a significant criterion for classification.
3	Household Income	Household Income	--	--	Journal papers focusing on residential energy consumption in the Indian context have suggested household income as a critical factor.

4	Occupancy	--	Household sizes	--	The number of people living in a dwelling may influence the energy consumption in the buildings.
5	HVAC Type	HVAC Type			Using air conditioners significantly contributes to the building's total energy consumption. This parameter will be addressed as a part of the "Equipment Ownership" criteria.
6	Area/size	Area/size	Number of rooms		The area/size of the building also demands more cooling/heating and illumination.
7		Equipment Ownership	Equipment /Asset		Indian studies focusing on residential energy have used equipment ownership to understand the consumption pattern.

While conducting the survey, data for the above-shortlisted parameters are collected for principal component analysis (PCA) to shortlist the parameters further. Different data types are collected from each household, including the data related to the parameters shortlisted above.

Data collection

The survey conducted in Jaipur was designed to investigate the finer aspects of energy consumption in Indian households. The study identified a list of parameters from the existing literature and tested its correlation with energy consumption. This paper elaborates on factors that nudge end-user's consumption behaviour and other related decisions that contribute to the same. The survey was limited to the municipal boundary of Jaipur. Hence, the climatic and cultural aspect of consumption was a constant for this study. The survey only considered census households with a legal electricity connection. The squatter settlements and semi-formal housing stock were not included in this sample. Random sampling was done to select the households for each income class and dwelling type. The survey study depends on user feedback to derive its conclusions. Independent sensor-based monitoring was not a part of this study. That is why equipment-based consumptions are represented in ranges instead of absolute values. The feedback was collected through structured and semi-structured questionnaires. The survey form is divided into three sections: the socioeconomic section, the equipment data section, and the geometric and construction data section. In each section, the different types of data points are included, which are listed in the table below.

Table 2: Classification of data collected through the survey

Categories	Description
Socioeconomic	Household size, Household income
Equipment	Ownership of equipment, Hours of operation [within a range], annual energy units consumed [actuals]
Geometric & Construction	Building type (single family unit, multifamily units, single/multi-storied unit), area, number of rooms, building envelop specification, Fenestrations (window types and material)

The samples were spatially distributed across the city in various residential neighbourhoods. The distributed sample collection locations and their percentage share are presented in Figure 2.

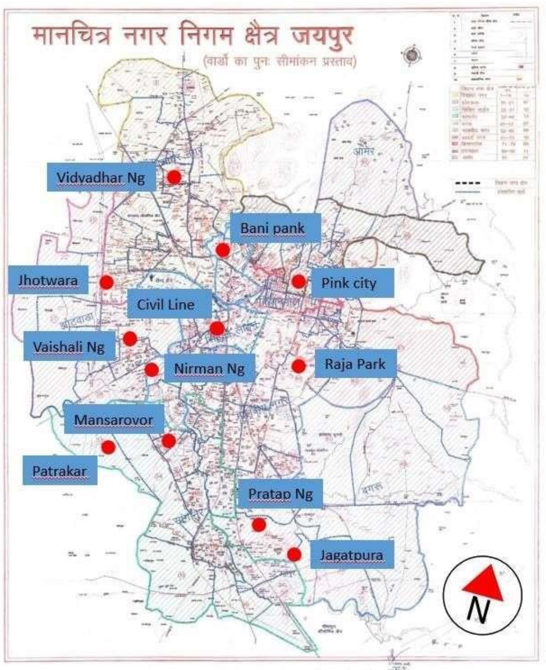

Figure 2: Sample distribution across Jaipur. Source of the map used: Jaipur Municipal Corporation (CC BY-NC)

Distribution of samples across various building types and BHK configurations

There are broadly three significant configurations of these building units:

1. Single-family units (both single-floor and multi-stories)
2. Multifamily Mid-rise Buildings (usually ground + 3 floors)
3. Multifamily High-rise Buildings (usually six floors and above)

The survey team aimed to gather data samples that accurately represent the full spectrum of residential buildings in Jaipur, encompassing both spatial and typological diversity. A comprehensive collection effort yielded 2345 samples from various locations throughout the city. Of these, only 2,327 samples were finally selected for further analysis. Table 3 shows the distribution of samples across various BHK configurations.

Table 3: Distribution of sample collected during the case study across different BHK Types

Sample required	**1536**	**For a 95% confidence level in each BHK type**
Samples collected	2345	Assuming 15-20% of samples may be lost due to unforeseen circumstances.
1 BHK	526	23 % of the total sample size
2 BHK	601	26 % of the total sample size
3 BHK	622	27 % of the total sample size
4 BHK	578	25 % of the total sample size
Total number of samples after eliminating the inconsistent samples	2327	

The survey samples include dwelling units from all floor levels. Many low- and middle-income families usually live in multi-storied apartments in Jaipur. There are also a good number of duplex units within the sample. These units are independent, two-storied buildings occupied by one household. Hence, they are treated as one single unit in the data set. During the survey, it was observed that most old habitable buildings had been renovated periodically. Thus, the building envelope has changed due to the application of new materials. Hence, the old building behaves like a new building despite being considered old by its occupant.

The household is classified into five broad income groups. This study has adopted the income classification from the PMAY program of the Government of India. The program classifies households into four groups, based on their income level, to provide them with appropriate housing assistance. The first group's income goes maximum up to 0.3 million INR per year; the second group lies between 0.3 to 0.6 million INR per year, the third group earns between 0.6-1.2 million INR per year, and the fourth group's income remains within the range of 1.2-1.8 million INR per year. A fifth income group was added to this study to bring more diversity to the sample. The fifth group includes a household income higher than 1.8 million INR per year. The figure below shows the distribution of samples across five income groups. Central government's housing schemes classify housing based on income. Housing allocations are done based on income levels. In addition, we found that in the real estate market, both for rental and purchase, dwelling units are usually classified in BHK terms. BHK stands for Bedroom (B), Hall (H), and Kitchen (K) dwelling configuration. Most units are often referred to as 1BHK, 2BHK, or 3BHK units, meaning a team with 1, 2, or 3 bedrooms. It is necessary to mention that these units do not necessarily have a standard size or shape.

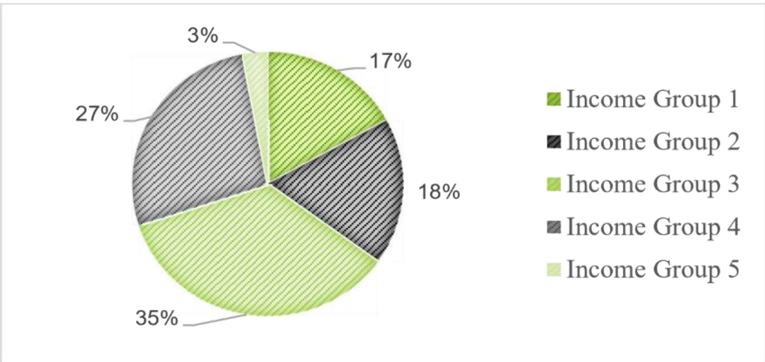

Figure 3: Percentage distribution of samples across income groups

Moreover, in CENSUS of India 2011, the dwelling units are also classified based on number of rooms. It makes this classification more practical. This study has four BHK types (1BHK, 2BHK, 3BHK, and 4BHK) that were considered for sampling. One of the prime objectives of this study was to understand the consumption pattern in Indian homes. As per the studies done by Prayas in 2008, 90% of the annual residential energy consumption was contributed by lighting, cooling, heating appliances (fans, evaporative coolers, room heaters, geysers, refrigerators, and air conditioners) and Television [7]. Though this study had made few assumptions, the broader range defined by this study was helpful. Similar studies by the World Bank [8] and NITI Aayog [9] have also found similar trends. However, a large-scale intrusive monitoring study must define these equipment-level consumption averages. Hence, for this case, only the devices mentioned above are considered for the survey. A wide range of variation is found in appliance ownership across various households from different socioeconomic backgrounds. Previous studies show that the equipment ownership pattern at the household level reveals the suppressed potential of growth in consumption levels soon [10] [11] [8] [9]. Hence, the paper presents an overview of the current state of equipment ownership reported during the survey.

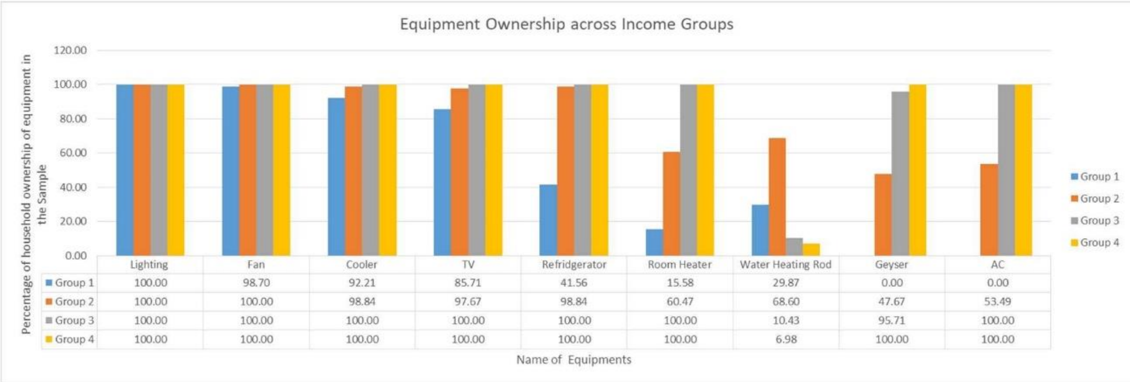

Figure 4: Equipment Ownership of different Income groups.

The survey only considers houses with formal electricity connecting with monthly bills only. The fan was available in almost all households except a few homes in the low-income class (only two houses were reported on fans). The evaporative cooler is one of the most used electrical appliances in homes in Jaipur, with a minimum ownership of 92%. To our surprise, even high-income homes (Group 4) also have evaporative coolers in Jaipur and use them to cool down large common spaces during the summers. In most cases, they prefer A.C. over evaporative coolers during the summers. It is important to note that many high incomes homes also have air-conditioners in the common areas. It shows critical aspects of user behaviours. Many low-income homes have old evaporative coolers bought from the second-hand market. Refrigerators have a moderate presence (only 41 %) in low-income houses (Group 1). Despite low-cost new models and good deals from the second-hand markets, low-income groups hesitate to buy this equipment due to the recurring monthly cost of consumption.

In some cases, households reported seasonal use of the equipment in low-income homes. Television has a very high penetration in almost all kinds of households. Some households reported (17 out of 451) mobile phones or laptops as preferred entertainment devices. Room heaters are rare among low-income families in Jaipur. Many said burning dry wood during winter for heat. However, in high-income homes, heaters are prevalent for warmth during winter. A very peculiar trend was found in geysers and immersion heating rods. The ownership of geysers increases with income level, and the ownership of immersion rods drops. Few high-income houses reported safety concerns over using immersion rods at home. Whereas in low-income homes, this was reported as quick and handy for heating water. All surveyed homes from Groups 3 and 4 (higher income band) own air-conditioners. In Group 2, only 53% ownership is found, whereas no household from Group 1 has air-conditioners. Extensive examples exist of multiple air-conditioners in one home from Groups 3 and 4 (high income). In some cases, people from Group 2 reported having used air- conditioners purchased from the second-hand market.

Table 4: Pearson correlation coefficients for each selected parameter

	Floor Level	BHK Type	Age of Building	Occupancy	Occupancy /Area	Income Class	Built-up area	Equipment Load	Load /Area	Target/output Variable	
										EPI	Annual Consumption
Floor Level	1.00	0.16	-0.29	0.12	-0.04	0.14	0.13	0.18	0.12	0.10	0.18
BHK type	0.16	1.00	-0.24	0.20	-0.52	0.79	0.55	0.88	0.78	0.66	0.89
Age of Building	-0.29	-0.24	1.00	-0.10	0.11	-0.28	-0.11	-0.29	-0.32	-0.28	-0.28
Occupancy	0.12	0.20	-0.10	1.00	0.60	0.09	0.02	0.15	0.13	0.12	0.15
Occupancy /Area	-0.04	-0.52	0.11	0.60	1.00	-0.55	-0.50	-0.52	-0.44	-0.30	-0.53
Income class	0.14	0.79	-0.28	0.09	-0.55	1.00	0.59	0.89	0.84	0.75	0.89

Built-up area	0.13	0.55	-0.11	0.02	-0.50	0.59	1.00	0.57	0.38	0.24	0.56
Equipment load	0.18	0.88	-0.29	0.15	-0.52	0.89	0.57	1.00	0.94	0.76	0.94
Load/Area	0.12	0.78	-0.32	0.13	-0.44	0.84	0.38	0.94	1.00	0.86	0.88
EPI	0.10	0.66	-0.28	0.12	-0.30	0.75	0.24	0.76	0.86	1.00	0.85
Annual consumption	0.18	0.89	-0.28	0.15	-0.53	0.89	0.56	0.94	0.88	0.85	1.00

Result and Discussion

A correlation matrix was generated for all the parameters selected in the preceding section. In addition to the previously identified parameters, several new variables were evaluated to enhance understanding of their correlation with annual energy consumption. Table 4 (correlation matrix) contains each parameter's Pearson correlation coefficient.

The income groups are transformed into corresponding numerical values arranged in ascending order. The numerical value of 1 indicated the lower socioeconomic stratum, denoted as group 1. Analogously, the values 2, 3, 4, and 5 corresponded to groups 2, 3, 4, and 5, respectively. Likewise, representative numerical values are assigned to the age of buildings. Parameters that exhibit an r-value greater than 0.5 are deemed significant and are subsequently chosen for further analysis. Notably, the correlation between energy consumption and two variables changed significantly upon factoring them in. The variable of household size exhibits a weak correlation (0.15) with energy consumption. Upon considering the developed space of the residential unit, its correlation coefficient increased to 0.53. In a separate instance, although the correlation between equipment loads and the area is considered, it is observed that the correlation between equipment load and energy consumption is only slightly reduced. When factoring variables of varying strengths, there is a possibility of significant correlation shifts when one variable is strong and the other is weak. However, the resulting correlation shift may be marginal if both variables are strong. The study has identified several key variables that significantly impact energy consumption in residential buildings. These variables include BHK types, occupancy per unit area, income class, built-up area, equipment load, and equipment load per unit area.

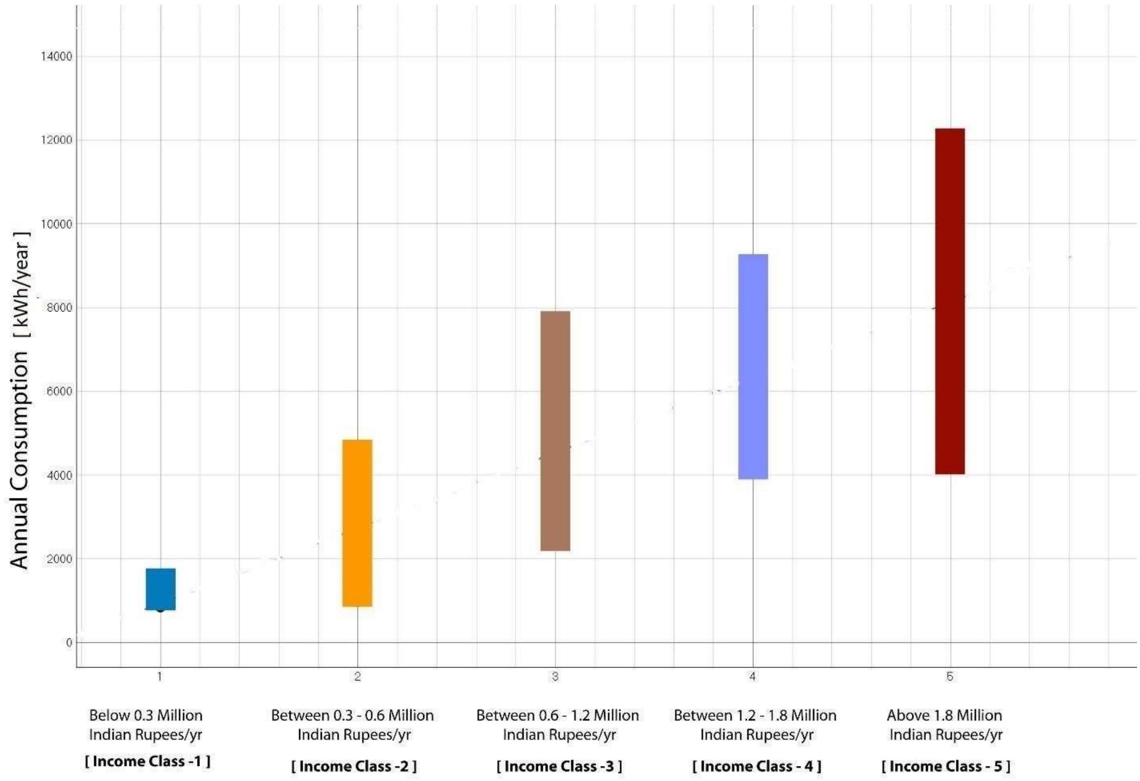

Figure 5: Income groups versus annual energy consumption

EPI and Annual Energy Consumption as an indicator of the energy performance of buildings

Notably, variation exists in the correlation coefficients of each parameter with the annual energy consumption and the Energy Performance Index (EPI), represented as the quotient of total annual energy consumption and the building's area. Remarkably, each parameter demonstrates a more robust correlation with annual consumption than the EPI metric.

Despite this, the EPI has assumed a pivotal role as a primary yardstick for evaluating building benchmarks. A particularly intriguing phenomenon arises when buildings sharing identical energy consumption profiles are assessed through the prism of the EPI metric. Such an analytical shift has the potential to engender divergent perceptions. Consequently, the energy-saving potential intrinsic to larger buildings might need to be more obscured solely due to their representation within the EPI framework.

Moreover, it's noteworthy that a higher occupancy density is accommodated within a confined built-up space within low-income households. Their energy consumption remains substantially lower compared to their counterparts in higher-income brackets. This observation underscores the potential limitations of the EPI as an all-encompassing indicator for capturing a building's comprehensive energy performance. The multifaceted nature of building energy dynamics calls for a nuanced approach when interpreting and selecting indicators. While the EPI has proven valuable, its reliability in portraying overall energy performance is context-dependent, necessitating careful consideration of the specific attributes under evaluation.

Household size

The survey found more individuals living in low-income dwelling units compared to the same dwelling unit with higher income classes. Despite that, the annual energy consumption levels are lower (in low-income units) than in the higher-income units with fewer people. Hence, more people in the household will consume less energy. There were examples of 6-8 people living in a 2BHK unit with very low consumption in low-income houses found during the survey. On the contrary, a similar 2BHK unit with higher income levels consumed more energy.

Household Income and Equipment Ownership

The income levels of households play a crucial role in influencing energy consumption behaviour. While discussing with consumers from various economic classes during the survey, we realized a deep psychological connection between wealth and equipment ownership. People show their economic well-being through new household appliance purchases. Hence, especially among the lower-income classes, the aspiration to own a refrigerator or an air-conditioner is some shot of an economic milestone.

Hence, while looking into the energy consumption aspect of equipment, the aspirational and psychological impact of such ownership must not be discounted. There is a strong consensus among the people for more consumption. Across all economic classes, there is an inherent aspiration to buy more and consume more for better comfort.

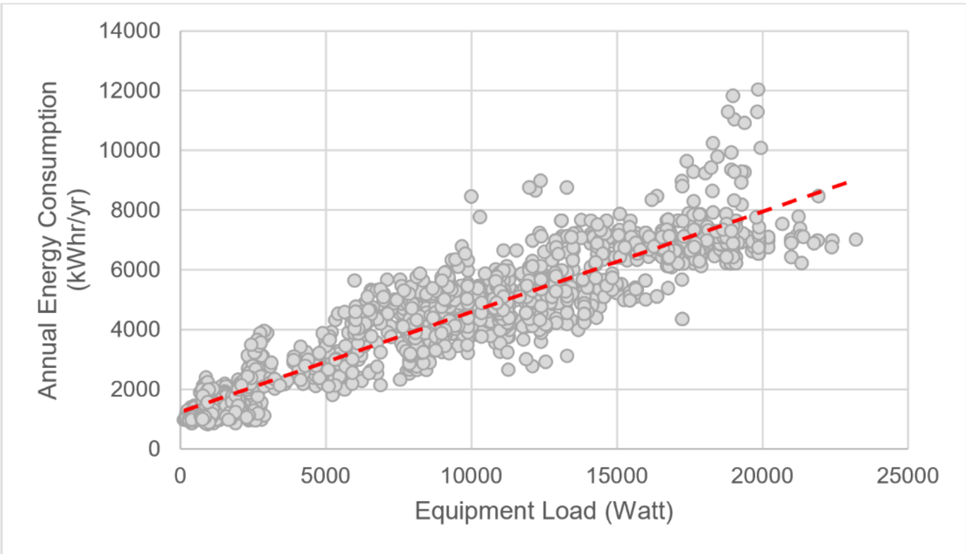

Figure 6: The figure depicts the correlation between equipment Wattage and annual energy consumption

However, higher income and equipment ownership only sometimes generate higher energy consumption. A wide variation in energy consumption is found within higher-income groups with higher equipment ownership.

Limitations and scopes for future studies

The scope of this study is restricted to examining residential buildings exclusively within the city of Jaipur. Consequently, the investigation is limited to a solitary climatic zone. Furthermore, the dataset employed in this research originates from a household survey, whereby information is garnered directly from participants. The operational schedules of appliances and other pertinent end-user details are derived from the responses provided by these participants. The future researcher may undertake similar studies in other geographic locations. It helps compare the impact of various parameters in different contexts. Moreover, IoT-based monitored datasets may be able to unfold the correlations with better accuracy. Additionally, studies may focus on different social groups (ethnic groups, caste-based groups, etc.) to understand their energy consumption behaviours.

Conclusion

Households exhibit varying energy consumption patterns, yet this study underscores the pivotal role of household income as a determinant shaping energy consumption patterns within Jaipur's residences. In the upcoming years, comprehensive large-scale investigations will be imperative to delve into the nuanced intricacies of end-user energy consumption patterns spanning urban and regional contexts. The collection of end-user energy consumption data across multiple strata holds paramount significance.

Amidst the survey, a prevailing aspiration for enhanced comfort resonated across all income brackets. This aspiration, coupled with the advancing efficiency of appliances and the burgeoning household incomes of the aspiring Indian middle class, augurs an exciting trajectory for India's energy landscape in the foreseeable future. Within our survey and subsequent data analysis, three pivotal insights emerged:

1. Establishing a standardized framework for conducting surveys is imperative, fostering data sharing within the research community. This approach is critical as equipment-level datasets are essential for refining statistical models and calibrating simulation outcomes.
2. Contrary to expectation, increased equipment ownership does not necessarily translate to rising energy consumption levels in the same proportion across all income groups.
3. Annual energy consumption is a viable alternative to the Energy Performance Index (EPI) as an indicator for evaluating building energy performance.

This study sheds light on the complexity of energy consumption behaviours and the influence of income, advocating for a holistic approach to data collection and refined metrics for effective energy management.

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